34. MECHANICAL SYSTEMS AND DIFFERENTIAL THROTTLING

By Charles F. Zalabak

Lewis Research Center, NASA

Table I is a list of several mechanical systems for achieving thrust vector control. In the left column are the more desirable schemes; in the right column are what at the moment appear to be the less desirable schemes. The early liquid rockets have employed the jetavators, jet vanes, and jet tabs. In general, they are too heavy for the current concepts of the liquid engines, and the modern engines have been gimbaled.

Under the gimbaled engine system are listed two types: (1) the conventional gimbal in which the thrust loads are effectively taken out at a point and which uses a relatively small gimbal bearing and (2) the cam ring. A part of the thrust structure, a cylindrical section with nonparallel ends, is rotated about its axis to provide thrust vectoring. In its more advanced form the cam ring can provide the same kind of angular motion of the thrust axis that a conventional system produces.

In the right column, the gimbaled chamber concept, first of the less attractive systems, may have promise for the can-annular plug engine. For liquid rockets regenerative cooling will be required, particularly in the high engine pressure regime, and the difficulties of sealing take the canted and the gimbaled nozzle out of the picture.

The net result is that gimbaling is the attractive form of vectoring among the mechanical systems. It is a proven concept. It appears to be the lightest. And studies by Aerojet and Rocketdyne indicate that there are no conceptual difficulties in extending the capabilities of the gimbaling system to a thrust level at least as high as 8 million pounds. Therefore, the remainder of this discussion will be largely confined to the gimbaling system.

Figure 1 is a very rough schematic, intended only to indicate the way the thrust loads of the various engine types might be transferred to the vehicle. The bell nozzle has already been described. Thrust loads are most conveniently taken out in a thrust cone.

In the forced deflection nozzle, thrust loads are distributed over a large diameter, lightweight structure; therefore, the thrust structure is most conveniently represented by a large diameter cylinder.

The same is true with the plug concept.

There are still many problems in regard to the gimbal system proposed for the M-1, which has a conventional bell nozzle; table II lists some of the items to be considered. In brackets at the top are the M-1 gimbal specifications - $\pm 7.5^{\circ}$, angular rate of 15° per second, and a ringing frequency of something greater than 7 cycles per second.

The problems associated with the gimbal design are listed: the suction lines, as they determine the length of the thrust structure and the inter stage;

the volume compensation requirement as it influences the length; the natural frequency as determined by the engine packaging and the gimbal-bearing radius; the gimbal bearing design and whether it is to be ball and socket or roller bearing; and the choice of an actuator, either hydraulic or pneumatic since we are now working with the cryogenics.

Figure 2 is a schematic of suction lines. At the bottom is a schematic representation of the F-1 type suction duct which has been used as a design basis for the M-1 engine. The forward and aft U-joints take the angular deflection of the suction joint, and the sections on either side of center take the axial deformation. The section in the middle provides axial expansion when the sections on each side undergo axial compression, and vice versa.

The length evaluations are depicted in the sketch at the top of the figure. The correction "called out" is the angle corresponding to the misalignment factors that occur because of unknown positions of the pump inlet and the tank flange. When the total vectoring angle is large compared to the angular capability of the U-sections, the length is determined by the differential angle $\theta-\delta$ and the amount of lateral displacement. With the differential first established the duct lengths required were extreme. It has since been determined that the angular capacity can be expected to be better than that initially used and acceptable duct lengths are the result.

When the angular capability becomes large enough, the determining length of the suction ducts is the volume compensator. From some studies in this area at Lewis and at Aerojet, it has been established that the need for volume compensation is relatively small; that it is quite reasonable to expect to have sufficient ullage pressure at the time that it is needed. The need is expected to occur only in the early stages of engine operation as the result of pressure surges associated with the maximum gimbal motion requirements.

As is indicated in figure 3, the natural frequency is proportional to the length of the lever arm (the normal distance between the gimbal center and the actuator attachment point), and to the square root of the ratio of the effective spring constant to the polar moment of inertia of the engine about its gimbal center.

The actuator can be designed with high enough stiffness that the effective spring constant is determined by the vehicle structure and the engine ring-and-tripod assembly at the actuator attachment points. With a specific value for the spring constant of the vehicle structure the engine ring-and-tripod assembly was varied to obtain the best combination of spring constant, weight, and actuator arm length.

Then the engine packaging was varied in order to lower the polar moment of inertia. The pumps were moved from station 1 to station 2. The inertia about the center of gravity was lowered. The gimbal center was relocated to position 2 by increasing the gimbal bearing radius. The net result was a reduction of the polar movement of inertia about the gimbal center. For an optimum arrangement of the actuator arm and ring-and-tripod assembly the natural frequency was about 5 cycles/second for the pumps-forward configuration and 7 cycles per second for the pumps-aft configuration.

Although the M-1 plan presently conceived does not include the development of actuators, some consideration was given to the area and some characteristics of various types of actuators are listed in table III. Gimbal actuator characteristics for the modern engines are presented in table IV. The actuators for the H-1, F-1, and RL-10 are hydraulic; those for the J-2 actuator represents those of a configuration in the early stages of development. We do not expect the weight of a pneumatic actuator for the M-1 to be extensively different. Certainly it would not be scaled up according to torque output and engine size. The primary difference would be the length of the stroke.

Figure 4 is a schematic of this actuator. It comprises a pneumatic motor driving a planetary transmission and ball screw. There would be no change in concept for M-1 application - only a resizing of the motor, primarily in speed, and a lengthening of the stroke.

In summary, the problem areas of the gimbaled design are shown in table V. The angularity limits that are imposed by the suction duct bellows result in high interstage and thrust structure weight due to excessive line length. The bellows design and material selection can be improved to give a higher degree of angular capability. Other concepts, for example, the arched suction line, in which the motion between pitch and yaw planes is separated, result in a larger angular capability.

A principal cause of natural frequency is the moment of inertia. This is a significant problem area with the bigger engines. As a result of lower natural frequency, there will be problems of coupling with the bending and slosh modes of the vehicle requiring greater control complexity. Solutions, as pointed out in the case of the M-1, are component arrangement and a larger gimbal radius. There are other concepts, one of which is the cam-ring gimbal, that attempt to solve the problem. The spring-mass system is characterizied by the inertia of a part of the thrust structure, and torsional vibration modes are excited.

Gimbal bearing friction plus the structural deflection of the engine can cause the control dead band and resulting control instability. Potential solutions are the selection of suitable materials and lubricant and the bearing design.

The effort involved in the solution of these problems appears to have been incidental to each engine design. It is possible that advanced technology effort in some of these areas could be very helpful.

The thrust vector can be controlled by throttling. Two modes of throttling are available and impose similar performance penalties regardless of engine type. One mode is that of plus and minus control for engines on each side of the vehicle axis, in which case the engines will be subdesign capability during the nonvectoring time periods. If engine thrust is decreased to the only freedom allowed, the total vehicular thrust oscillates with vectoring requirement.

With the conventional-bell engine vector, control by throttling is limited to multi-engine configurations. The control capability can be determined from the thrust axis and vehicle geometry and the degree of throttling. In the case of the forced-deflection nozzles with multichambers, the work to date indicates

only small corrections are available. The same is true for can-annular plug configurations. The capability can be increased by increasing the control complexity. For instance, control over half the periphery improves the capability, but with pitch-yaw control require a significant complexity problem is imposed on the controls. Experimental results indicate a decrease in vectoring capability for increasing nozzle-pressure ratios.

To define the area of applicability of thrust-vector control by throttling, experimental studies should be made on the forced-deflection and can-annular plug configurations to establish the performance at high pressure ratios. The desirability of a vehicle with this capability should be evaluated. Also, there is a need to establish the feasibility of vehicle operation with large axial thrust variations that result from throttling.

TABLE I

MECHANICAL SYSTEMS FOR THRUST-VECTOR CONTROL

GIMBALED ENGINE
- CONVENTIONAL
- CAM-RING
- HYDRAULIC-SLIPPER

JETAVATORS

JET VANES

JET TABS

GIMBALED CHAMBER

GIMBALED NOZZLE

CANTED NOZZLE

ASYMMETRIC NOZZLE EXTENSION

TABLE II

M-1 GIMBAL DESIGN

$\left[\pm 7\frac{1}{2}^{\circ},\ 15^{\circ}/\text{SEC},\ f_n \geq 7\ \text{CPS}.\right]$

SUCTION LINES
- LENGTH
- VOLUME COMPENSATION

NATURAL FREQUENCY
- ENGINE PACKAGING
- GIMBAL-BEARING RADIUS

GIMBAL BEARING
- BALL AND SOCKET
- ROLLER

ACTUATOR
- HYDRAULIC
- PNEUMATIC

TABLE III

ACTUATOR COMPARISON

HYDRAULIC	WELL DEVELOPED, PROVEN RELIABILITY, CAPABLE OF BEING SCALED TO SIZES REQUIRED, HAS REQUIRED STIFFNESS, REQUIRES TEMPERATURE CONDITIONING AND AN AUXILIARY PUMP.
PNEUMATIC	OBTAINABLE WITH APPROPRIATE POWER CAPABILITY, DOES NOT NEED TEMPERATURE CONDITIONING OR AUXILIARY POWER SOURCE, STIFFNESS IS A PROBLEM IN SOME CONCEPTS, IS NOT WELL DEVELOPED.
ELECTROMECHANICAL	MOST APPROPRIATE FOR SMALL SYSTEMS, MANY RESTARTS, FOR APPLICATIONS WITH READY SOURCE OF ELECTRICAL POWER.

TABLE IV

ENGINE-GIMBAL-ACTUATOR CHARACTERISTICS

	H-1	F-1	RL-10	J-2	M-1
GIMBAL RANGE, DEG	±7.5	±6	±3	±7.5	±7.5
OUTPUT TORQUE, FT-LB	18,300	380,000	2,770	34,800	557,280
OUTPUT VELOCITY, DEG/SEC	19	10	8	9	15
ACTUATOR WEIGHT, LB	22.5	300	8.9	75	150
ENGINE THRUST	190K	1.5M	15K	200K	1.5M

TABLE V

PROBLEM AREAS IN GIMBAL SYSTEMS

	PRINCIPAL SOURCE	CONSEQUENCES	SOLUTIONS	EFFORT
1. ANGULARITY LIMITS	SUCTION-DUCT BELLOWS	HIGH INTER-STAGE AND THRUST STRUCTURE WEIGHT DUE TO EXCESSIVE LINE LENGTH	BELLOW DESIGN, MATERIAL SELECTION, IMPROVED CONCEPTS (E.G., ARCHED-LINE CONFIGURATION)	INCIDENTAL TO EACH ENGINE DEVELOPMENT
2. NATURAL FREQUENCY	MOMENT OF INERTIA	COUPLING WITH BENDING AND SLOSH MODES, CONTROL COMPLEXITY	COMPONENT ARRANGEMENT AND GIMBAL RADIUS TO REDUCE MOMENT OF INERTIA, IMPROVED CONCEPTS (E.G., CAM-RING GIMBAL)	
3. CONTROL DEAD BAND	BEARING FRICTION PLUS STRUCTURAL DEFLECTION	INSTABILITY	MATERIALS AND LUBRICANT SELECTION, BEARING DESIGN	

THRUST-LOAD DISTRIBUTION

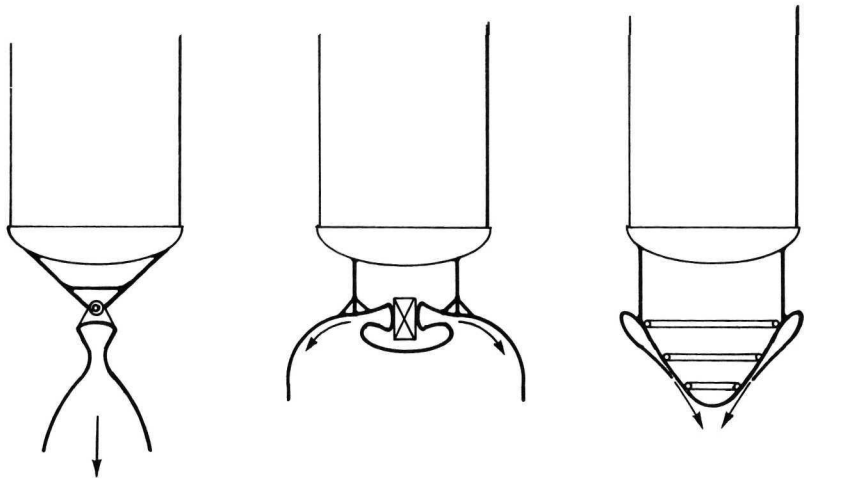

Figure 1

SUCTION LINE-LENGTH DETERMINATION

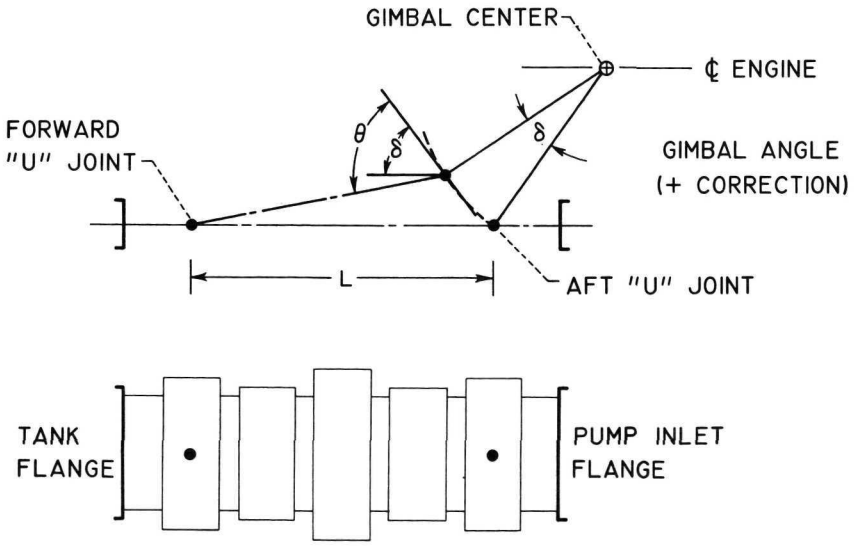

Figure 2

NATURAL FREQUENCY REQUIREMENT

$f_n \propto$ LEVER ARM $\sqrt{\frac{\text{SYSTEM SPRING CONSTANT}}{\text{POLAR MOMENT OF INERTIA}}}$

($f_n \geq 7$ CPS FOR M-1)

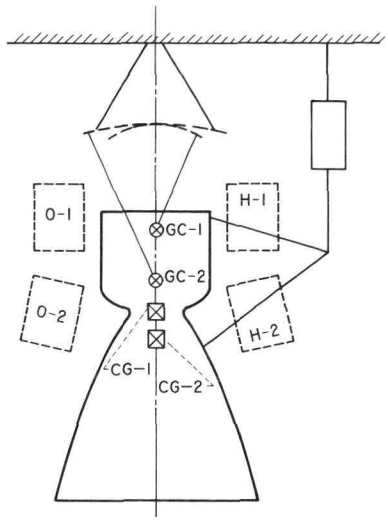

Figure 3

PNEUMATIC GIMBAL ACTUATOR

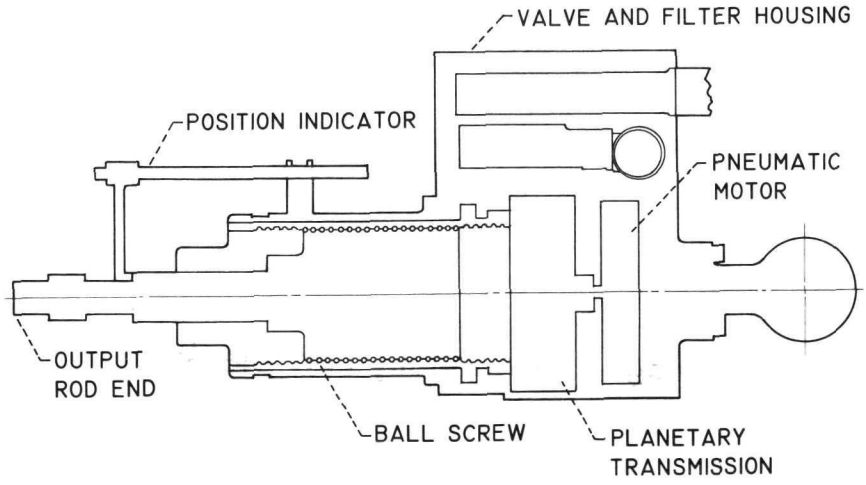

Figure 4